

Are monopoles hiding in monopolium?

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Abstract

Dirac showed that the existence of one magnetic pole in the universe could offer an explanation of the discrete nature of the electric charge. Magnetic poles appear naturally in most Grand Unified Theories. Their discovery would be of greatest importance for particle physics and cosmology. The intense experimental search carried thus far has not met with success. I propose a Universe with magnetic poles which are not observed free because they hide in deeply bound monopole–anti-monopole states named monopolium. I study the feasibility of this proposal and establish signatures for confirming my scenario.

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1 Introduction

The theoretical justification for the existence of classical magnetic poles, hereafter called monopoles, is that they add symmetry to Maxwell's equations [1] and explain charge quantization [2]. Dirac showed that the mere existence of a monopole in the universe could offer an explanation of the discrete nature of the electric charge. His analysis leads to the so called Dirac Quantization Condition (DQC),

$$\frac{eg}{\hbar c} = \frac{N}{2}, \quad N = 1, 2, \dots, \quad (1)$$

where e is the electron charge and g the monopole charge. Note that if quarks were asymptotic states the minimum monopole charge would be three times larger.

The origin of monopoles, and therefore their properties, is diverse. In Dirac's formulation monopoles are assumed to exist as point-like particles and quantum mechanical consistency conditions lead to Eq.(1), establishing the value of their magnetic charge. However, their mass, m , is a parameter of the theory, limited only by classical reasonings to be $m > 2 \text{ GeV}$ [3]. In non-Abelian gauge theories monopoles arise as topologically stable solutions through spontaneous breaking via the Kibble mechanism [4]. They are allowed by most Grand Unified Theory (GUT) models, have finite size and come out extremely massive $m > 10^{16} \text{ GeV}$. Furthermore, there are also models based on other mechanisms with masses between those two extremes [3, 5, 6].

The discovery of monopoles would be of greatest importance not only for particle physics but for cosmology as well. Therefore monopoles and their experimental detection have been a subject of much study since many believe in Dirac's statement[2]

"...one would be surprised if Nature had made no use of it [the monopole]."

At present, despite intense experimental search, there is no evidence of their existence [3, 5, 7, 8, 9]. This state of affairs has led me to investigate a possible mechanism by which monopoles could exist and still be undetectable by present experiments.

Despite the fact that monopoles symmetrize in form Maxwell's equations there is a numerical asymmetry arising from the DQC, namely that the basic magnetic charge is much larger than the smallest electric charge. This led Dirac himself in his 1931 paper [2] to state,

"... the attractive force between two one quantum poles of opposite sign is $(\frac{137}{2})^2 \approx 4692\frac{1}{4}$ time that between the electron and the proton. This very large force may perhaps account for why the monopoles have never been separated."

This latter statement sets the philosophy of my scenario: at some early stage in the expansion of the Universe, monopoles and their antiparticles were created;

at that time, the dynamics was such that, soon thereafter, most of them paired up to form monopole-anti-monopole bound states called monopolium. With time, monopolia become more and more bound until their constituents annihilate. However, the mean life of monopolium is sufficiently long to allow monopolia to exist even today in measurable abundances. Thus today, most of the existing monopoles, appear confined in deeply bound states [10]. Monopolia have produced observable signatures during their formation period, a remnant isotropic radiation, and provide us with direct evidence of their present existence in the form of Ultra High Energy Cosmic Rays (UHECR) and localized low frequency radiation from within the core of the clusters of galaxies[11, 12] .

2 Hidden monopoles

I proceed to describe the proposed scenario. Mine is a phenomenological approach. I envisage a scenario, which is realized by means of a few assumptions, in which monopoles are not observable as free states at present, that satisfies all experiments and leads to new observations which can sustain it. What cosmological models realize the proposed scenario is for the present investigation of no relevance.

At some early stage in the expansion of the Universe monopoles and their antiparticles were created by a mechanism which is free from the standard monopole problem [13]. No precise mechanism for their creation is advocated, therefore the mass is not fixed and is left as a parameter to be fitted by consistency requirements. Moreover, (anti)monopoles existed in the Universe, at that time, at the level of abundance compatible with known phenomenological and experimental upper bounds [14, 15, 16]. Most of the (anti)monopoles bind in pairs during nucleosynthesis, due to the strong magnetic forces, to form monopolium. This fundamental hypothesis of my scheme is realized physically by the following condition,

$$r_{capture} \ll \lambda. \quad (2)$$

Here λ is the mean free path of the monopoles in the hot plasma,

$$\lambda \sim \frac{1}{\sigma \rho_{ch}}, \quad (3)$$

where σ is the cross section for the scattering of the monopole with charged particles [3, 10]

$$\sigma \sim 2 \frac{mc^2}{kT} \text{ nanobarns}, \quad (4)$$

ρ_{ch} the density of charged particles and m is the mass of the monopole; and $r_{capture}$ is the capture distance of the monopole [3, 10],

$$r_{capture} \sim \frac{g^2}{kT}. \quad (5)$$

Furthermore, I describe the monopoles from the monopolium formation era up to the present days by point like Dirac monopoles. It is reasonable to do so since the discussion is largely independent of the detailed structure of the monopoles because it depends only on global properties, i.e., magnetic charge, mass and cosmological abundances.

In the rest of the paper I proceed to show that my assumptions lead to a picture consistent with data.

I describe monopolium as a Bohr atom, with reduced mass $m/2$ and a strong magnetic, instead of a weak electric, coupling. Its binding energy is

$$E \sim \left(\frac{1}{8\alpha}\right)^2 \frac{mc^2}{n^2}, \quad (6)$$

where $\alpha = \frac{1}{137}$ is the fine structure constant of QED and n the principal quantum number. This equation and those that follow are to be considered only for large principal quantum number ($n > 50$). For low values of n the annihilation mechanism becomes dominant.

The approximate size of the system is given by

$$r \sim \langle r \rangle_{n,0} \sim \frac{12\hbar}{mc} \alpha n^2. \quad (7)$$

To calculate the mean life I distinguish two processes, i) the cascading process, dominated by dipole radiation [11], which I apply as

$$\tau_{dipole} \sim \frac{2m^2 c \alpha_n^3}{\hbar^2} \sim 2 (12)^3 \frac{\hbar}{mc^2} \alpha^5 n_i^6, \quad (8)$$

where n_i is the principal quantum number associated with the initial bound state which will be very large $n_i \sim 10^9$; ii) the annihilation process, which due to the magnitude of g is highly non perturbative and which I next estimate. Looking at the two photon decay process I see [17, 18]

$$\tau_{annihilation} \ll \tau_{2\gamma} \sim 2 (4)^5 \frac{\hbar}{mc^2} \alpha^5 n_f^3, \quad (9)$$

where n_f is the largest principal quantum number associated with a state at which annihilation is still efficient. Since the monopole and anti-monopole only annihilate efficiently when there is a considerable probability of being on top of each other and this only happens for $n < 50$, $n_f \ll n_i$. Thus the annihilation mean life is small compared with the cascading time and can be disregarded in the time scale analysis.

The previous equations can be summarized in terms of the binding energy of the initial bound state and the mean life as,

$$E_b(eV) r_b(\text{\AA}) \sim 5 \cdot 10^4 eV \text{\AA} \quad (10)$$

$$n_i \sim 9 \cdot 10^4 [E_b(eV)^{1/4} \tau(sec)^{1/4}] \quad (11)$$

$$mc^2(eV) \sim 3 \cdot 10^7 [E_b(eV)^{3/2} \tau(sec)^{1/2}] eV. \quad (12)$$

Here E_b and r_b are respectively the binding energy and the radius of the initial bound state.

Using Eqs. (2) through (12) my scenario can be constructed. I assume that capture takes place for a binding energy slightly higher, to avoid thermal dissociation, than $kT = 1$ MeV,

$$E_b > 1 \text{ MeV} . \quad (13)$$

This temperature is not related to the scale for production of monopoles but to that at which monopolium, the bound state, is formed from already existing monopoles [11].

From these equations monopolium is a tightly bound system

$$r_b < 0.05 \text{ \AA} < r_{\text{capture}} \sim 0.3 \text{ \AA} . \quad (14)$$

The solution of the remaining equations require a recurrent process since they are all intertwined. Consistency has been achieved for the following values.

I obtain for the mean life of monopolium, τ , defined from τ_{dipole} ,

$$\tau_U / \tau \sim 100 , \quad (15)$$

where τ_U is the age of the Universe.

Capture happens at a very outer shell,

$$n_i \sim 5 \cdot 10^9 , \quad (16)$$

and the mass of the monopole comes out,

$$mc^2 \sim 5 \cdot 10^{15} \text{ GeV} , \quad (17)$$

which justifies the non relativistic treatment for large n and is surprisingly very close to the mass of the GUT monopole.

Finally I obtain my crucial assumption satisfied as

$$r_{\text{capture}} \sim 0.3 \text{ \AA} \ll \lambda \sim 5.6 \text{ \AA} , \quad (18)$$

where I have used that for $kT \sim 1$ MeV the density of charged particles is [13]

$$\rho_{ch} \sim 1.8 \cdot 10^{21} \text{ particles/cm}^3 . \quad (19)$$

It was pointed out that the drag force felt by the monopole in the plasma reduces dramatically the mean life of the state [20]. This effect is not active in my scenario since Eq.(2), realized as Eq.(18), produces a terribly small monopolium which feels a negligible drag force [20].

I have just shown that the proposed scenario is realized in this naive scheme. I proceed next to investigate phenomenological consistencies of the proposed picture.

3 Monopolium abundance

Monopolium has been associated with UHECR in various schemes [11, 12, 20]. This association leads to a phenomenological determination of its abundance. In here I look for consistency between the phenomenological determined abundances and the monopolium mean life obtained in my calculation.

What is the present number of monopolia? From the simple observation that the mass density due to monopolia should not exceed the limit on the mass density of the Universe imposed by Hubble's constant and the deceleration parameter one gets, following Preskill[19], for their density,

$$\rho_{today} \sim 3. \cdot 10^{-18} \text{ monopolia}/cm^3 . \quad (20)$$

Is this number reasonable?

If I restrict the number of decays of monopolia to a few thousand per year and per cubic parsec, a conservative estimate in agreement with observational limits [11], I get

$$\rho_{today} \sim 10^{-40} \text{ monopolia}/cm^3 , \quad (21)$$

in agreement with the estimate of ref.[20]. I take the second estimate as more reasonable since it arises from observation. A collateral result of the calculation is that monopolia do not contribute greatly to the mass of the universe.

Is ρ_{today} consistent with the used mean life?

In order to find out I have to calculate the number of monopolia at formation. If I assume the standard scenario for nucleosynthesis that requires that monopolia do not dominate the mass of the Universe at that time one gets [19],

$$\rho(kT = 1\text{MeV}) \sim 5. \cdot 10^{13} \text{ monopolia}/cm^3 , \quad (22)$$

which gives a density for today of

$$\rho_{today} \sim 10^{-40} \text{ monopolia}/cm^3 . \quad (23)$$

using $\rho(t) = \rho(0)e^{-\tau_U/\tau}$ for $\tau_U/\tau \sim 100$.

Thus, within the validity of my scheme the two numbers, Eqs. (21) and (23) are compatible.

A more sophisticated calculation following ref. [19] shows that monopole-anti-monopole annihilation is halted by the expansion of the Universe. To achieve the same monopolia abundances, a shorter mean life is necessary, which results in a better verification of my fundamental Eq.(2) and thus to a more complete disappearance of free monopoles in the early Universe in favor of monopolia.

I conclude from the above analysis that at present most monopolium states are close to the annihilation levels, $n_f \sim 50$, and therefore their binding energy is huge, at the level of

$$E_b > 10^{14} \text{ GeV} \quad , \quad (24)$$

supporting Dirac's conjecture for the non observability of monopoles.

4 Monopolium detection

My discussion would be semantic if the existence of monopolium could not be tested independently of the detection of monopoles. My estimates for the density of monopolia at present are similar to those for which monopole detectors have been built. Moreover, monopolium is easier to detect than monopoles themselves, because it is a bound state and therefore one can use in addition spectroscopic methods.

Cascading from large values of n leads to a Larmor type spectrum

$$\lambda_{\text{radiation}} \sim 16\alpha^2 \frac{h}{mc} n_n^3 \sim 32 \frac{\text{eV}}{mc^2} n^3 \text{ \AA} \quad , \quad (25)$$

which for large values of n , where the formula is certainly applicable, extends all the way into radio frequencies. Experiments should look for a diffuse isotropic radio background as a remnant from the nucleosynthesis period.

The core of galaxies, and of clusters of galaxies, provides us with an environment of high density and energy where the existing monopolia can be excited. One can therefore have a glimpse on the high frequency part of the spectrum. Also, monopolia may be broken up there, and (anti)monopoles might be liberated, forming immediately thereafter lightly bound monopolia, which cascade down slowly, by present time scales, to its annihilation regime showing the low frequency part of the spectrum.

Monopolium can annihilate, at the level of a few thousand per year and per cubic parsec, providing a huge amount of energy, $E > 10^{15} \text{ GeV}$, in a small region of space-time which will produce UHECRs in what Hill [11] calls a cataclysmic scenario, whose details depend on the microscopic theory of monopole formation. Since the mean life of monopolium is at least two orders of magnitude smaller than the age of the Universe, these observations result from the tale of the original population. Furthermore, showers of remnants from the more numerous past annihilations should also be detectable.

Monopolium has properties, like magnetic polarizability and magnetic multipole moments, which could be very interesting for laboratory detection using the Lorentz and "dual" Lorentz force laws. Since large electric fields are easier to construct than large magnetic fields the dual Lorentz force might be instrumental for monopolium detection in the laboratory.

5 Conclusions

The possibility of having (anti)monopoles in Nature is appealing. I have presented a scenario for the Universe in which primordial (anti)monopoles exist still today however, not as free particles, but deeply bound in monopolium states. The crucial ingredient of my proposal is that the mean free path of monopoles is much larger than their capture radius and therefore they bind so tightly in monopolium that they barely interact with the surrounding plasma, surviving in this way the effect of the drag force.

Two distinctive quantities determine the consistency of the various requirements, the temperature of monopolium formation ($kT \sim 1$ MeV) and the mean life of the state ($\tau < 10^9$ years). The outcome is an extremely massive particle protected from the interaction with the medium in a strongly bound state, which ultimately annihilates in a cataclysmic scenario giving rise to UHECRs. The mean life of monopolium is at least two orders of magnitude smaller than the age of the Universe, thus one is contemplating only the decay of the tale of the original population. Showers of remnants of the numerous past annihilations should be also detectable.

The detection of monopolia, and therefore the existence of monopoles, presents interesting signatures associated with the monopolium spectrum, i.e., a diffuse isotropic radio frequency background, localized (galaxies) high frequency excitation and monopolium formation spectrum, and isotropically distributed very energetic gamma rays associated with monopolium annihilation.

Finally, the electromagnetic properties of monopolium, associated with the dual character of the electromagnetic interaction in the presence of monopoles, are instrumental for designing new laboratory experiments.

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